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Review of modelling details in relation to low-concentration solar concentrating photovoltaic

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ABSTRACT

This paper reviews solar cell performance influenced by increased irradiance. The response of PV cell parameters to low level of concentration is analysed. Solar cell's parameters influenced by high temperature as a result of increased irradiance will be investigated. Different types of heat removal arrangement are proposed. Using computer simulation, PV cell's behaviour is analysed and presented.

Contents

1. Introduction

Public awareness, need for reducing climate change, and an interest in living a greener lifestyle have created interest and support in renewable energy amongst both authorities and member of public in the past ten years. As a result of this interest and support, utilization of renewable energy in general and solar energy in particular has been rapidly increasing. One of the technologies to utilize sun energy is solar photovoltaic (PV), which is conversion of sun light directly into electricity. Photovoltaic systems convert sunlight into electricity, based either on flat-plate photovoltaic modules or concentrating photovoltaic (CPV) modules [1]. Direct conversion of solar radiation into electrical energy is the most convenient way of utilizing solar energy. Using the photovoltaic effect to generate electricity has many advantages including no emission production during operation, low-maintenance, long lifetime of operation. Moreover, solar energy is plentifully available, free, clean and available in any part of the world. The basic device of a PV system is the silicon solar cell. When sunlight falls on PV cells, it just acts like a chemical battery. You get electrical power out of it for as long as the sun shines on it. Unlike a battery, it never wears out, as long as the sun is shining [2]. Cells may be grouped to form panels or arrays. The voltage and current available at the terminals of PV device may directly feed small loads. More sophisticated applications require electronic converters to process the electricity from PV device [3].

The high production cost of solar cells has been a major hindrance to the technology's market penetration. Concentrating PV uses concentrated sunlight to achieve a cost-effective solar energy.

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Nomenclature

G	solar irradiance (W/m^2)
a	diode ideality factor no fix value between 1 and 1.5
R_s	series resistance
R_{SH}	shunt resistance
T_C	cell temperature
J_{SC}	Silicon's short circuit current density
J_o	Silicon's dark saturation current density
$J_{SC} = 31.188 \times 10^{-3}$ A/cm^2	short circuit current density at STC
$J_o = 1 \times 10^{-12}$ A/cm^2	saturation current density at STC
STC	AM = 1.5, G = 1000 W/m^2, cell temperature $T_{cell} = 25\,^\circ$C
V_T is thermal potential	$V_T = \frac{k \times T}{q}$
Boltzmann's constant	$k = 1.38066 \times 10^{-23}$ J/K
Electron charge	$q = 1.602 \times 10^{-19}$ C
T	absolute temperature
V_T	thermal voltage, $V_T \approx 0.0258$ at room temperature
I_L	light-generated current
V_{OC}	open circuit voltage = 0.623 at STC
I_{SC}	silicon's short circuit current
I_o	silicon's dark saturation current
G_{ref}	is irradiation on the solar cell surface at STC, which is 1000 W/m^2
$I_{SC_{ref}}$	is light-generated current at STC
T_{ref}	is temperature in Kelvin at STC
NOCT	nominal operating cell temperature

Concentrating photovoltaic (CPV) technology is quite different from the flat plate PV module. CPV units come in larger module sizes, typically 20–35 kW, track the sun during the day, and are more suitable for larger installation [4].

2. Concentrating photovoltaic

Concentrating photovoltaic (CPV) operates based on the concept of concentrating sunlight. Concentrators such as optic lens and mirrors are used to concentrate sunlight onto a small area of solar cells. There are many different arrangements to increase the illumination density on the surface of solar cell. Fig. 1 shows a flat plate solar PV. Enhanced flat plate mirrors on sides shown in Figs. 2 and 3 are simple examples of enhancing solar radiations. Solar cell in this example of linear CPV receives direct radiation as well as solar radiations reflected from the both sides. CPV are characterized by high efficiency, low system cost, low-capital investment, can play the role of major contributor to the future clean electricity [5]. The performance of solar cells strongly depends on the availability of solar irradiance at location and the solar cells temperature. Thus, reliable knowledge and understanding of the solar cells performance under different operating conditions and at different radiation levels is of great importance for accurate prediction of their performance. An accurate model helps us to better understand the behaviour of cell parameters under different operation conditions and radiation level, particularly at increased cell temperature as a result of increased sun radiation. This can increase the illumination intensity by factor up to 10. Using lens can increase illumination intensity much higher.

2.1. Advantages of concentrating PV

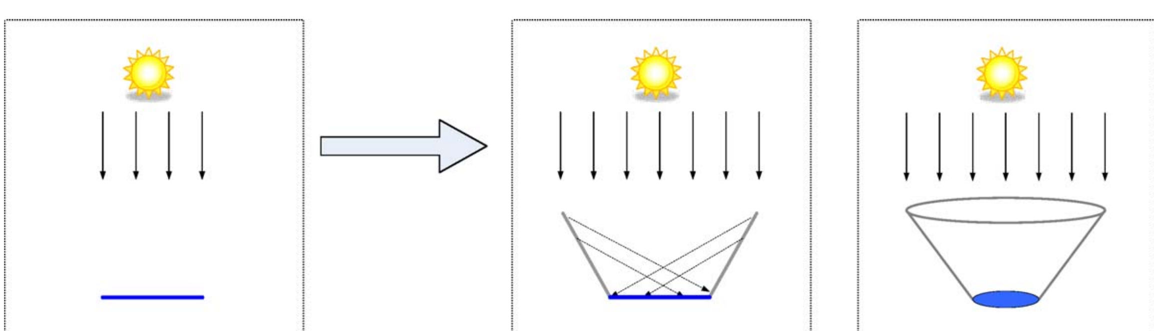
- Concentrating PV replaces expensive silicon solar cell silicon, or GaAs solar cells with low-cost materials such as glass, mirror, and plastic. This reduces the total solar cell area.
- Solar cells are more efficient at high concentration.
- Electricity production by CPV can start earlier and extend later in the day due to tracking.
- Concentrators use less cell material in a PV system. PV cells are the most expensive components of a PV system. A concentrator makes use of relatively inexpensive materials such as optic lenses and mirrors to capture the solar energy shining on a fairly large area and focusing that energy onto a smaller area, where the PV cell is.

2.2. Disadvantages of concentrating PV

- Operating temperature of solar cells increases as sunlight is concentrated. Cell voltage is sensitive to temperature and in fact silicon solar cell has negative temperature coefficient. As a result of this solar cells lose efficiency, so CPV needs cooling system, particularly at high concentration levels.
- Concentrating systems only use direct sunlight, so they require an accurate sun tracking system, particularly at high concentration levels.

CPV system design is a balance of cost, efficiency, and complexity. System cost is lower, and system efficiency is higher, but system is more complex and must be equipped with an accurate tracking and requires thermal management. The output power from solar CPV systems depends on weather and environmental conditions. Therefore their output power fluctuates depending on weather conditions. As the solar CPV are larger in size, therefore power fluctuations might have some negative impacts on the grid to which CPV is connected [6].

This paper focuses on low-concentration concentrating PV, which can be obtained by enhancing edge of solar cells using mirrors. Two configurations of low-concentration concentrating PV are shown in Figs. 2 and 3. The two configurations can increase the irradiance by factor up to 10.



Figs. 1–3. (Fig. 1) Flat plate conventional solar cell. (Fig. 2) Reflective enhanced edge, linear. (Fig. 3) Reflective enhanced edge, circular.

3. Thermal effects on solar cell characteristics

Thermal management has always been an important issue for both one-sun flat-plate, and concentration system applications.

Photovoltaic cells only convert a small (less than 20%) portion of the sunlight to electricity [7]. The remaining photons are dissipated in the cells as heat. This heat must be dissipated efficiently otherwise it will result in a higher cell temperature, which in turn leads to a significant decrease in the cells efficiency. In order to avoid long-term damage the silicon cells should be kept below 60 °C.

Efficiency reduction as a result of temperature increase is mainly due to a decrease in open-circuit voltage (V_{oc}), which has negative temperature coefficient.

In fact the temperature affects all of the parameters in the solar cell's characteristic equation (Eq. (1)), but temperature effect on two parameters, namely V_{OC} and I_o is far more significantly than the others [7].

$$J = J_{SC} - J_o(e^{V/aV_T} - 1) \tag{1}$$

In Eq. (1), J_{SC} is silicon short circuit current density and J_o is silicon dark saturation current density, and a is diode ideality factor.

The value of current generated by silicon solar cell can be written as follows:

$$I = \frac{J_{SC}A}{1000}G - J_oA(e^{V/aV_T} - 1)$$

or

$$I = I_L - I_D = I_L - I_o(e^{V/aV_T} - 1) \tag{2}$$

Diode saturation current

$$I_D = I_o(e^{V/aV_T} - 1)$$

Temperature will influence the PV cell characteristic in two ways: directly, via T in the exponential term of Eq. (2), which is (e^{V/V_T}), and indirectly via temperature effect on the saturation current (I_o). While increasing T reduces the magnitude of the exponent in the characteristic equation, the value of I_o increases with increased temperature. The net effect is that the open-circuit voltage linearly reduces with increasing temperature. For most crystalline silicon solar cells the reduction is about 0.30%/°C to 0.50%/°C [7].

As increase in illumination intensity is associated with the increase of cell temperature, therefore for further modelling of PV system, we need to study the solar cell behaviour as a result of increase in irradiation conditions and temperature. For this purpose Section 5 of this paper focuses on the open circuit voltage and diode saturation current, which are more sensitive to temperature than the other parameters.

4. Ideal model of PV

Basic equation from the theory of semiconductors, which mathematically describes relationship between cell's voltage and current density of photovoltaic cell, is given in Eq. (1). A simple, 3-parameter solar cell model is shown in Fig. 4 [8].

This equation is known as I–V characteristics of silicon solar cell. In this equation I_L is called light generated current and is equal to short circuit current (in ideal solar cell) and is directly proportional to irradiance G as follows:

$$I_L = \frac{J_{SC}A}{1000}G, \quad I_L = I_{SC}$$

Open circuit voltage: $V_{OC} = V_T \mathrm{Ln}(I_L/I_o + 1)$ or $V_{OC} = V_T \mathrm{Ln}((J_{SC}/J_o) + 1)$, $V_{OC} = 0.6234\,\mathrm{V}$ under standard testing conditions. The values of $V_{OC}$and I_{SC}, are power influenced by irradiance as shown in Figs. 2 and 3.

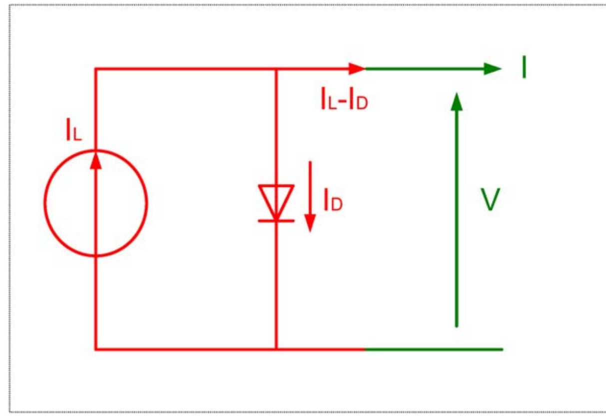


Fig. 4. Model of an ideal PV cell.

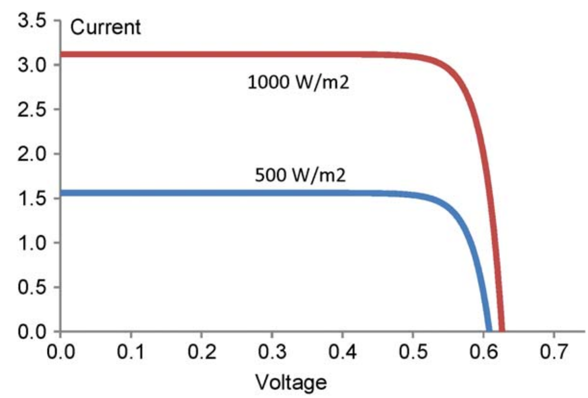


Fig. 5. I–V characteristics of a PV cell for two irradiance levels.

Dark saturation current in terms of short circuit current is $I_o = I_{SC}/(\mathrm{EXP}(V_{OC}/aV_T) - 1)$

Fig. 5 shows the non-linear relationship between voltage and current of PV cell. These two quantities are highly dependent on solar irradiance incident on PV cell. Fig. 6 shows that the relationship between power and voltage of PV cell is also a non-linear relationship and is highly dependent on solar irradiance incident on the solar cell. Fig. 7 shows that I–V curve of solar cell depend on solar temperature. As temperature increases the area under the curve, which represents PV power decreases. Fig. 8 shows P–V curve for four different cell temperatures.

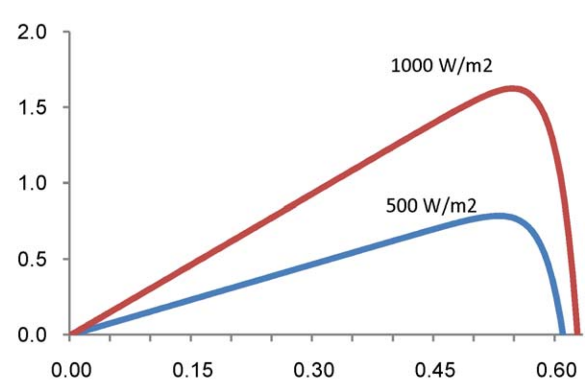


Fig. 6. P–V characteristics of a PV cell for two irradiance levels.

Table 1
The data used to perform the irradiance and temperature analysis.

T_a	NOCT	T-ref	k	q	$J_{SC\text{-ref}}$	$J_{o\text{-ref}}$	$V_{T\text{-ref}}$	$V_{OC\text{-ref}}$	K_v	K_i
20	40	25	1.4E−23	1.6E−19	0.0312	1.0E−12	0.0252	0.610	−0.0023	0.0035

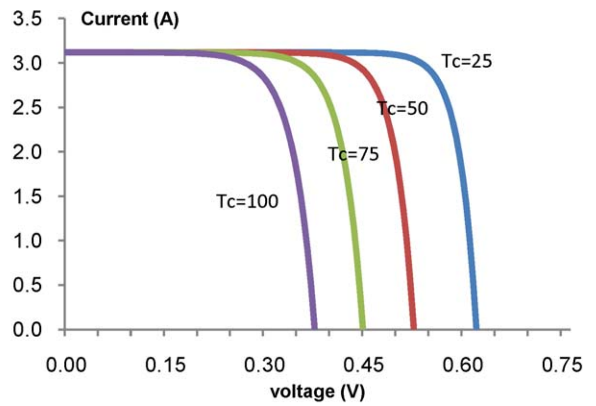


Fig. 7. *I–V* characteristic curve of solar cell for 4 different temperatures (irradiance: 1000 W/m^2).

5. Effects of increased irradiance and temperature

The value of G in Eq. (3) depends on the concentration level of CPV. The solar cell current I_L (light-generated current), which is assumed to be the same as short circuit current depends on the solar irradiance (G) and is also influenced by the cell temperature according to following equation:

$$I_{SC} = \frac{I_{SC_{ref}}(1 + K_t \Delta T)G}{G_{ref}} \tag{3}$$

It is assumed that temperature increase has negligible effect on short circuit current, while open circuit voltage in influenced significantly. The new solar cell temperature as a result of increased irradiation is expressed according to the following equation [7]:

$$T_c = T_a + \frac{NOCT - 20}{800} G$$

T_c and T_a are cell and ambient temperature.

The diode saturation current I_o varies with temperature and can be expressed according to Eq. (4).

$$I_o = \frac{I_{SC}}{\exp(V_{OC(1+K_v \Delta T)}/aV_T) - 1} \tag{4}$$

$$\Delta T = T_c - T_{ref}$$

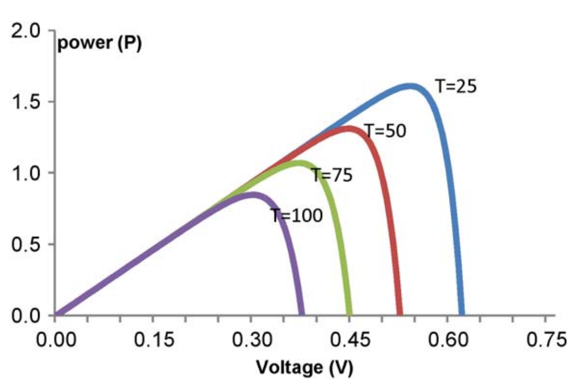


Fig. 8. *P–V* characteristic curve of solar cell for 5 different temperatures (irradiance: 1000 W/m^2).

The new relationship between current and voltage of solar cell influenced by the temperature can be expressed according to Eq. (5). In this equation changes in short circuit current as a result of temperature increase is ignored.

$$I = I_{SC_{ref}} \frac{G}{G_{ref}} - \frac{I_{SC}}{\exp(V_{OC(1+K_v \Delta T)}/aV_T) - 1}(e^{V/aV_T} - 1) \tag{5}$$

And also relationship between power and voltage of solar cell influenced by the temperature can be expressed according to Eq. (6).

$$P = V \times \left(I_{SC_{ref}} \frac{G}{G_{ref}} - \frac{I_{SC}}{\exp((V_{OC(1+K_v \Delta T)}/aV_T)) - 1}(e^{V/aV_T} - 1) \right) \tag{6}$$

6. PV performance under increased irradiance

The PV model described in the previous section can be improved if we do consider the effect of temperature increase on short circuit current.

$$I_{SC} = I_{SC_{ref}}(1 + K_i \Delta T) \frac{G}{G_{ref}} \tag{7}$$

The new relationship between current and voltage of solar cell can be expressed according to Eq. (8).

$$I = I_{SC_{ref}}(1 + K_i \Delta T) \frac{G}{G_{ref}} - \frac{I_{SC}}{\exp(V_{OC(1+K_v \Delta T)}/aV_T) - 1}(e^{V/aV_T} - 1) \tag{8}$$

And also the new relationship between power and voltage of solar cell can be expressed according to Eq. (9).

$$P = V \times \left(I_{SC_{ref}}(1 + K_i \Delta T) \frac{G}{G_{ref}} - \frac{I_{SC}}{\exp((V_{OC(1+K_v \Delta T)}/aV_T)) - 1}(e^{V/aV_T} - 1) \right) \tag{9}$$

Fig. 9 shows variation of *I–V* curve with irradiance, while Fig. 10 shows variation of *I–P* curve with irradiance.

According to the SAM [1] the NOCT is about 40 °C. Table 1 shows the data used to perform the irradiance and temperature analysis.

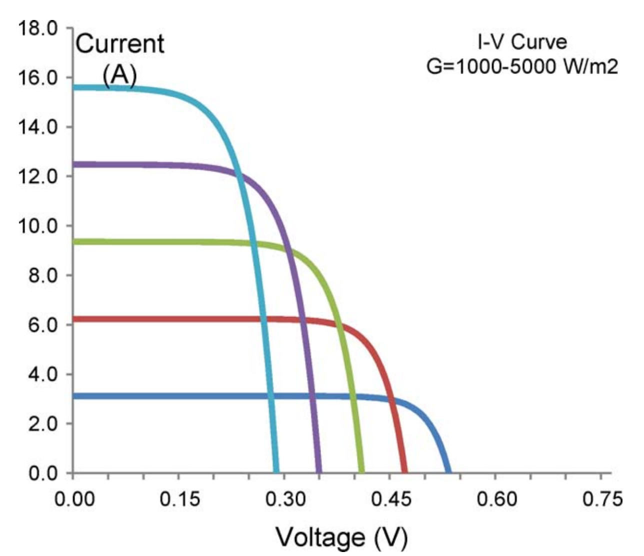


Fig. 9. *I–V* characteristic curve of solar cell for irradiances: 1000–5000 W/m^2, NOCT = 40 °C.

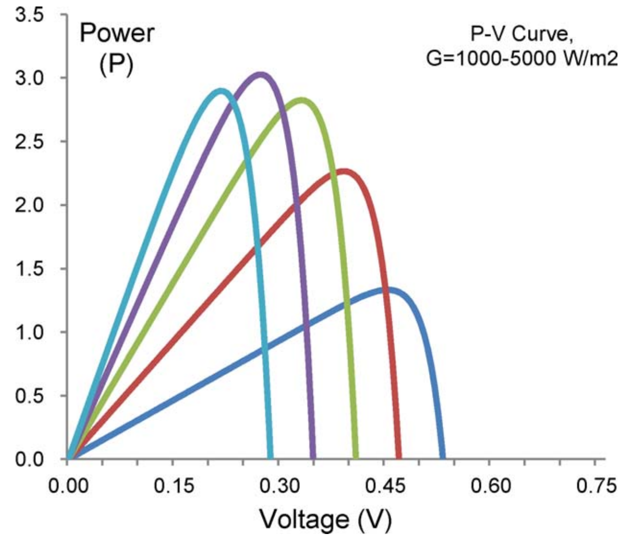


Fig. 10. *P–V* characteristic curve of solar cell for irradiances: 1000–5000 W/m^2, NOCT = 40 °C.

Table 2
Variation of cell's parameters with irradiance from 1000 to 5000 W/m^2.

G (W/m^2)	1000	2000	3000	4000	5000
G-ref (W/m^2)	1000	1000	1000	1000	1000
$V_{OC\text{-ref}}$ (V)	0.61	0.61	0.61	0.61	0.61
T_{cell} (°C)	45	70	95	120	145
ΔT (°C)	20	45	70	95	120
$V_{T\text{-New}}$ (V)	0.0274	0.0295	0.0317	0.0339	0.0360
$J_{SC\text{-ref}}$ (A/m^2)	0.0312	0.0312	0.0312	0.0312	0.0312
J_{SC} (A/m^2)	0.0312	0.062	0.0936	0.125	0.156
J_o (A/m^2)	1.16E−10	7.93E−9	2.4E−7	4.36E−6	5.41E−5
V_{OC} (V)	0.532	0.449	0.373	0.300	0.229

Table 2 shows variation of cell's parameters with irradiance from 1000 to 5000 W/m^2. Fig. 11 shows cell's temperature variations with irradiance.

7. Cooling options

Cooling of photovoltaic cells is one of the main concerns when designing concentrating photovoltaic systems. However, only a fraction of the incoming sunlight striking the cell is converted into electrical energy, the rest is absorbed as heat by solar cell. Heat can be removed from the back of solar cells by some heat removal technologies including passive cooling or water cooling. In passive cooling, heat is dissipated by natural cooling and natural convection, while in the case of high irradiance and high temperature, heat is removed from the back of solar cell by a water cooling system. Fig. 12 shows proposed natural cooling for low concentration PV system and Fig. 13 shows proposed water cooling system for higher concentration.

Because concentrators focus all of the light onto one highly illuminated area, all of the heat must therefore be removed through the back of the cells, which makes cooling in these systems a challenge. At concentration levels of 10 and above, air cooling is not sufficient, thus there is a need for a forced cooling system that uses water, for example.

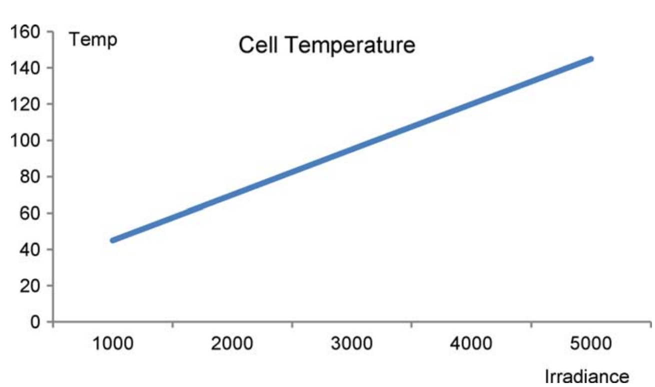


Fig. 11. Variation of cell temperature with irradiance.

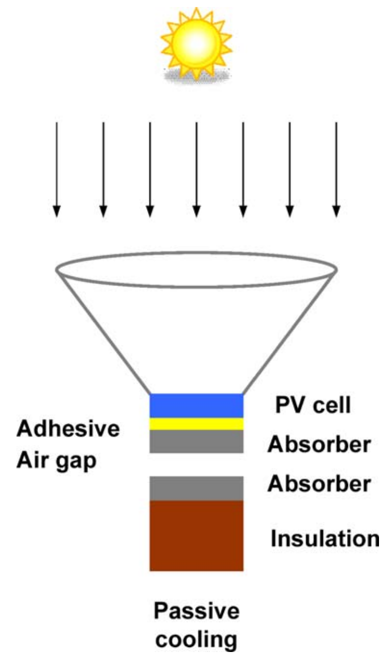


Fig. 12. Passive cooling.

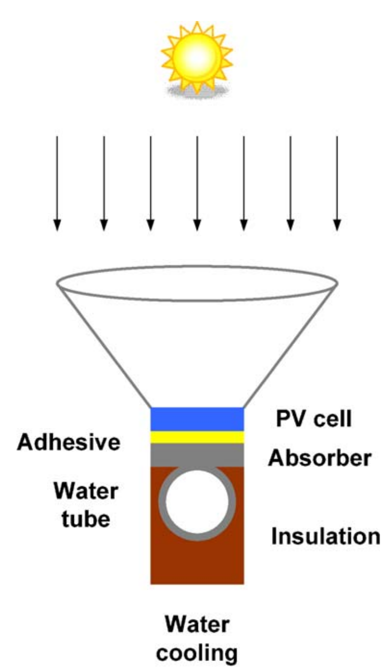


Fig. 13. Water cooling.

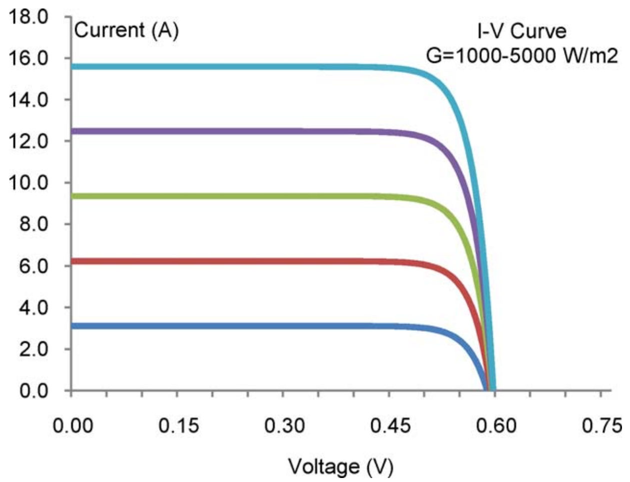


Fig. 14. *I–V* characteristic curve of solar cell for irradiances: 1000–5000 W/m^2, T_{cell} = 30 °C.

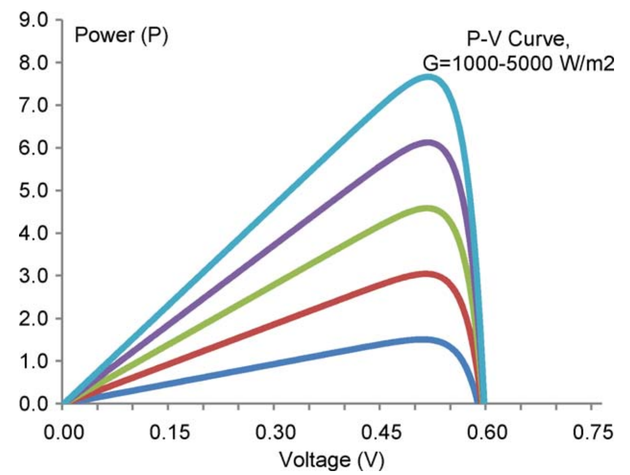


Fig. 15. *P–V* characteristic curve of solar cell for irradiances: 1000–5000 W/m^2, T_{cell} = 30 °C.

8. Improved performance

In case the cooling process is sufficient to bring cell's temperature back to normal operating temperature, then solar cell will be able to produce its expected power. This has been shown in Figs. 14 and 15.

9. Conclusions

This paper has reviewed and analysed low concentration PV systems, which use less solar cell materials and can produce low-cost electricity. Mathematical model proves that enhanced flat plate mirrors on side can increase the illumination density. Using solar cell and mirrors can increase the illumination density by factor 10 without need for cooling system. Low concentration of up to 10-sun creates small thermal problems. However, at high-concentration level active cooling system such as water cooling is required. This will be future activity of this work.

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